

OUTDOORS MEASUREMENTS OF PV MODULE EFFICIENCY AND TEMPERATURE COEFFICIENTS

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ABSTRACT: Performance of a PV installation depends critically on the modules behaviour. That is the reason why a good estimation of energy production of a PV installation relies not only on the goodness of the module power characterization at standard test conditions, but also on the goodness of the characterisation of the module behaviour related to the variation of irradiance and temperature. So, it is closer to the reality running a simulation exercise of energy production with the actual values measured outdoors than with the values obtained from datasheets. This paper presents a device specifically implemented to measure outdoors the power of modules at standard test conditions, as well as their efficiency variation with irradiance and their temperature coefficients. Results of measurements with this device are also reported.

Keywords: PV module, module efficiency, temperature coefficients, module characterisation.

1 INTRODUCTION

From the first large PV plants built ten years ago until today, the reduction of PV devices prices (mainly PV modules) and the reliability of these systems have supposed that such installations have gone from being built under the protection of feed-in tariff to become an interesting financial product that can compete directly in the energetic market [1] [2]. Therefore, nowadays the bankability of a PV plant is a fundamental requirement for its definite implementation [3]. Accurate models and parameters are required to achieve an energy yield forecast closer to the reality that guarantees the investments in this kind of systems. In fact, there are different commercial software packages developed in order to execute these estimations [4]. Unfortunately, most of them rely on complex equations and make use of numerous parameters which cannot be easily obtained in the field for large PV plants. Besides, these parameters are not adequately supported by PV module manufacturers, because they customarily restrict their guarantee to the data included in the datasheet, especially to the power at Standard Test Conditions (STC) of the individual PV modules, P^* .

Obviously, the performance of a PV installation depends critically on the modules behaviour. That is the reason why a good energy estimation relies not only on the goodness of the module power characterisation at standard test conditions (STC), but also on the goodness of the characterisation of the module behaviour related to the variation of irradiance and temperature. So, it is closer to the reality running a simulation exercise of energy production with the actual values measured than with the values obtained from datasheet. Actually, there is an international standard [5] that proposes to obtain the PV module performance at 4 cell temperature (from 15°C to 75°C) and at 7 irradiance levels (from 100W/m² to 1100W/m²). Nevertheless, this procedure is clearly defined for the characterisation with a solar simulator inside a laboratory, where is possible to measure quickly the 22 *I-V* curves required and to control the changes of irradiance and cell temperature needed. Besides, these devices are very expensive and the laboratories that can perform this kind of characterisation use to be far away from the PV plants.

PVCROPS (Photovoltaic Cost rēduction, Reliability, Operational performance, Prediction and Simulation) is a project within the European 7th Framework Programme which addresses these lacks [6]: it has developed a free software for energy yield forecast called SISIFO [7] [8] [9] that just relies on the information that could be guaranteed by manufacturers and has also proposed some tests procedures and devices to measure outdoors and on-site those module parameters [10] [11].

First, this paper slightly presents the model in which SISIFO is based and the parameters that are needed to get a good accuracy in the energy yield forecast. Then, a cheap device specifically implemented by the PVCROPS team which allows measuring outdoors those parameters (the module power at standard test conditions, the efficiency variation with irradiance and the temperature coefficients) is also presented. The results of measuring a module for a whole year and the results of measuring some batch of modules in this box are also reported.

2 THE ENERGY YIELD FORECAST SOFTWARE DEVELOPED BY PVCROPS: SISIFO.

SISIFO (SImulación de SIstemas FOtovoltaicos, in Spanish –in English, photovoltaic systems simulation) is a software package developed by the IES-UPM inside the PVCROPS project in order to estimate the energy production of a PV system. SISIFO relays on a simple PV module model based on the variation of its power with the irradiance and the temperature:

$$P_{DC}(G_{ef}, T_c) = P^* \frac{\eta(G_{ef}, T_c)}{\eta^*} f_{DC}$$

where the superscript * means STC, P_{DC} is the DC power delivered by the PV array, G_{ef} is the effective global solar irradiance in the plane of the array, T_c is the cell temperature, P^* is the nameplate DC power (obtained from the manufacturer's information), η means efficiency and f_{DC} is a coefficient that lumps together all the additional system losses in DC, e.g., technology-related issues, wiring, soiling and shading. In this equation:

$$\frac{\eta(G_{ef}, T_C)}{\eta^*} = \frac{G_{ef}}{G^*} [1 + \gamma \cdot (T_C - T_C^*)] [a + b \frac{G_{ef}}{G^*} + c \cdot \ln \frac{G_{ef}}{G^*}]$$

Where $G^* = 1000 \text{ W/m}^2$, $T_C^* = 25^\circ\text{C}$, γ is the thermal losses coefficient (a value which is always found at manufacturer datasheets), and the three parameters, a , b and c , describe the efficiency dependence on irradiance. It is interesting to note that concerned parameters (P^* , γ , a , b and c) are not only given at the information datasheet, but also considered as a part of the design qualification international norms (a , b and c are obtained from module power corresponding at three irradiance values, which must also be found at datasheets, providing they comply with international standards) [12] [13] [14].

This equation properly defines the performance of a PV array with high accuracy as demonstrated by other authors [15].

The AC power at the output of the PV system from this DC power at the inverter entry is

$$P_{AC} = P_{DC} \eta_{INV} f_{AC}$$

where P_{AC} is the AC power output of the PV array, η_{INV} is the efficiency of the inverter (which can be estimated from several values characteristics of its load curve), and f_{AC} is a coefficient that lumps together all the additional system losses in AC, e.g., technology-related issues and wiring.

Finally, the energy produced during a period of time T (a year, for example) is given by:

$$E_{AC} = \int_{t=0}^{t=T} P_{AC} dt$$

More information about the SISIFO software package can be found in the literature [7] [8] [9].

So, as can be noticed in the second equation, not only a good characterization of P^* but also of the coefficient of power variation with the temperature, γ , and of the parameters a , b and c to describe the efficiency dependence on irradiance are needed to get an accurate estimation of energy production, even when low irradiances are involved. As it has been said previously, this task uses to be done in laboratories which are able to perform these measurements with a solar simulator controlling the irradiance and cell temperature. But this implies to send the modules to the facilities of the laboratories, which use to be far away of the installation. This implies an overcost due to the roundtrip transport of the modules from the PV installation to the laboratory, as well as an additional risk of breakage related to this transport.

3 THE CLIMATIC BOX.

In order to reduce these additional costs and risks the IES-UPM, inside the PVCROPS project, has designed and implemented a cheap device (Climatic Box) that can be built anywhere a PV installation has been constructed to test modules and characterize their behaviour on-site at STC and/or in the actual meteorological conditions of the location in which the PV modules are going to operate.

Fig. 1 to Fig. 4 show this climatic box, which has been made of wood, in order to be robust, and which is filled with white polystyrene to isolate the inside of the

box and to decrease the heating of the whole box once the cover is removed (this cover is totally of polystyrene, lined with a thin reflective layer to avoid overheating of the inside and reinforced with wooden slats, so it is lighter and allows opening the box easier).



Figure 1: Climatic box developed by the IES-UPM for the testing of PV modules outdoors.

The PV module inside the climatic box is cooled down below 25°C with an external climatic device (white, at the left side of the box, Fig. 2). 9 temperature sensors (PT1000) attached to the PV module back sheet are used to monitor its temperature in 9 different points, among which are those indicated in international standards [5] [16].

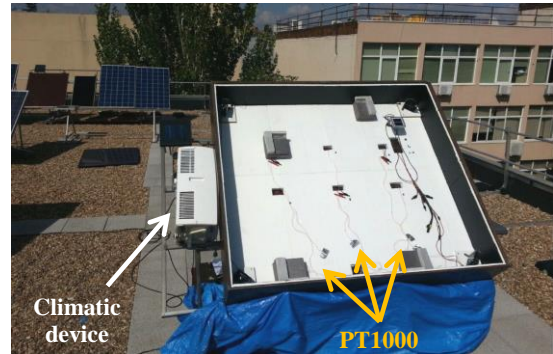


Figure 2: Climatic box opened. It is cooled down with an external climatic device and it has 9 PT1000 sensors to monitor the modules.

Four fans are located in the corners of the box to homogenize the temperature inside the box once the module is cooled down. A reference solar cell is also included inside the box to measure the incident irradiance (Fig. 3).

As the box is mounted on a tracking structure, it can be manually positioned (tilt and azimuth) and an external solar cell helps to move it until incident irradiance is very close to 1000 W/m^2 . Then, the box cover is retired, which forces the PV module placed inside to operate almost at STC (G^* and T_C^* , Fig. 4). An $I-V$ curve is then recorded with an electronic curve tracer [17] [18] [19] [20] and later adjusted to precise STC, using the incident irradiance given by the primary solar cell, also placed inside the box, and the PV module temperature given by the 9 temperature sensors attached to the PV module back sheet. These 10 values of irradiance and temperatures must be recorded with a datalogger simultaneously to the $I-V$ curve acquisition.

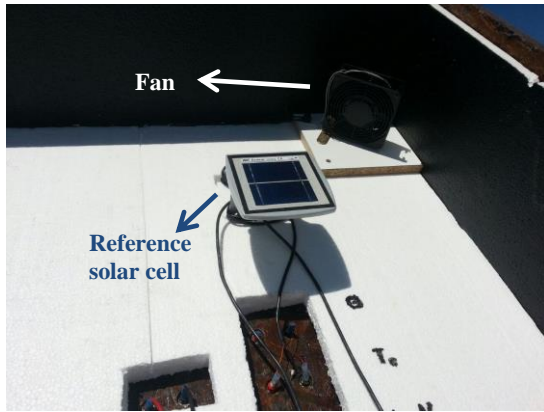


Figure 3: Reference solar cell to measure the incident irradiance and one of the four fans to homogenize the temperature inside the box before it is opened.



Figure 4: Module inside the solar box prepared to be measured at STC.

4. MEASUREMENTS INSIDE THE CLIMATIC BOX.

4.1 Measurement of electrical parameters at STC.

Fig. 5 to Fig. 8 show the results of measuring along a whole year the I - V curves at STC of a PV module inside the Climatic Box with the electronic curve tracers designed and implemented by the IES-UPM staff [11] [19] [20].

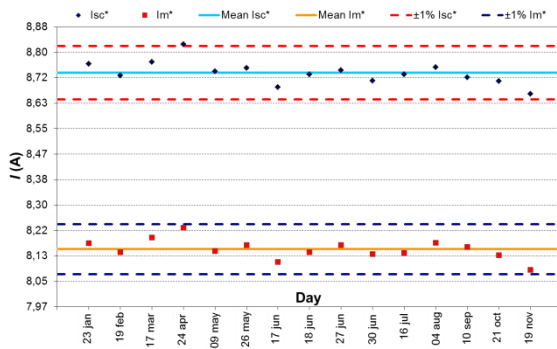


Figure 5: I_{SC}^* (blue diamonds) and I_M^* (red squares) of a PV module measured 15 times along a whole year inside the Climatic Box. The continuous lines represent the mean values of all the measurements and the dotted lines represent the deviation of 1% respect to these values.

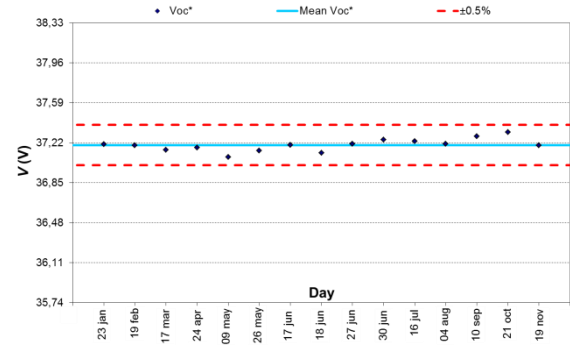


Figure 6: V_{OC}^* of a PV module measured 15 times along a whole year inside the Climatic Box. The continuous line represents the mean value of all the measurements and the dotted lines represent the deviation of 0.5% respect to the mean.

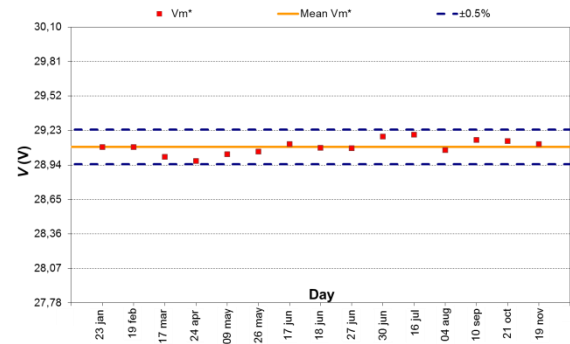


Figure 7: V_M^* of a PV module measured 15 times along a whole year inside the Climatic Box. The continuous line represents the mean value of all the measurements and the dotted lines represent the deviation of 0.5% respect to the mean.

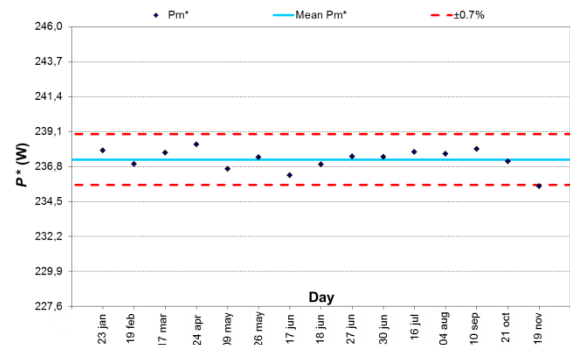


Figure 8: P_M^* of a PV module measured 15 times along a whole year inside the Climatic Box. The continuous line represents the mean value of all the measurements and the dotted lines represent the deviation of 0.7% respect to the mean.

As can be seen, repeatability of the measurements is very good: all the values of I_{SC}^* , I_M^* , V_{OC}^* , V_M^* and P_M^* are inside a range of $\pm 1\%$ (or even better) regarding the associated mean values. Besides, differences between these values and the result of the measurement done by a recognized laboratory are lower than 2%, which is the typical value obtained in round-robin procedures between different European laboratories [21] [22].

4.2 Measurement of temperature coefficients.

As it has been explained in the previous section, the Climatic Box allows measuring the electrical characteristics at STC. But if we continue obtaining I - V curves of the PV module once the cover of the Climatic Box is removed, the solar radiation heats the PV module until the equilibrium temperature is reached (roughly about 30°C over the ambience). Heating rate is between 3 to 6°C per minute, which is slow enough to record up to 25 I - V curves along the process, allowing the measurement of the PV module power, current and voltage temperature coefficients. Fig. 9 to Fig. 11 show an example of the results of such measurements.

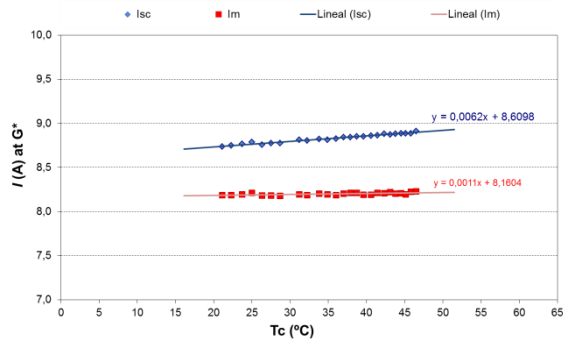


Figure 9: I_{SC} and I_M values (corrected to G^*) of a PV module versus operation temperature. These values have been obtained from 25 I - V curves measured with the module placed inside the Climatic Box.

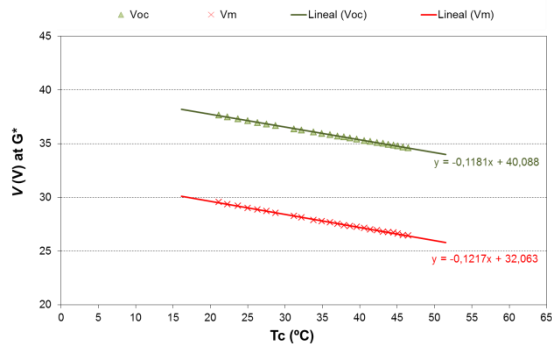


Figure 10: V_{OC} and V_M values (corrected to G^*) of a PV module versus operation temperature. These values have been obtained from 25 I - V curves measured with the module placed inside the Climatic Box.

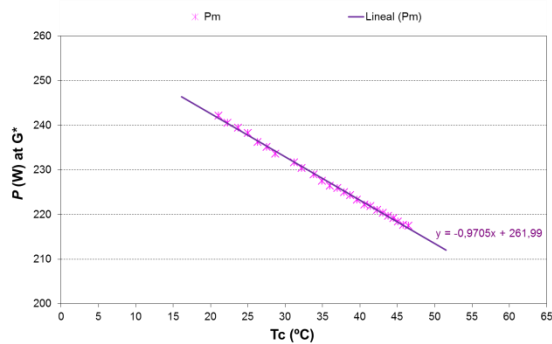


Figure 11: P_M values (corrected to G^*) of a PV module versus operation temperature. These values have been obtained from 25 I - V curves measured with the module placed inside the Climatic Box.

As can be seen, the trend related to temperature of the different variables is totally lineal. The uncertainties of these parameters obtained in the measurements outdoors along the full year are: $\pm 0.02\%/^{\circ}\text{C}$ for I_{SC}^* , I_M^* and V_{OC}^* ; $\pm 0.03\%/^{\circ}\text{C}$ for V_M^* ; and $\pm 0.04\%/^{\circ}\text{C}$ for P_M^* . These results are coherent with the values obtained by other authors [22], [23] [24].

These coefficients must be measured for the calibration of reference PV modules in order to reduce uncertainty and deviations in effective irradiance (coefficient related to I_{SC}^* , α) and in cell temperature (coefficient related to V_{OC}^* , β), because the values reported by the manufacturer could differ from the actual ones for every single module [5] [16] [24].

But these coefficients are not only needed for the calibration of reference modules. They are also appreciated to achieve more accurate energy estimations of the PV installation, reducing the uncertainty of such predictions (coefficient related to P_M^* , γ , in the case of SISIFO, see second equation) Therefore, a good energy estimation relies not only on the goodness of the module power characterization at STC, P_M^* , but also on the goodness of the characterization of the module behaviour related to the variation of temperature, γ . So, it is closer to the reality running a simulation exercise of energy production with the actual values measured over a sample of the modules that are going to be installed in the PV system than with the values directly obtained from manufacturer's datasheet [24].

Fig. 12 shows the result of measuring the temperature coefficient γ of a sample of 7 modules belonging to a batch of modules that is going to be installed at a real PV plant. In this particular case, the individual values are similar and close to the datasheet value ($-0.41\%/^{\circ}\text{C}$), but they differ slightly one from another one. So, better than use the manufacturer value of γ for the energy estimation is to use the mean value obtained from real measurements over a representative sample of the PV installation.

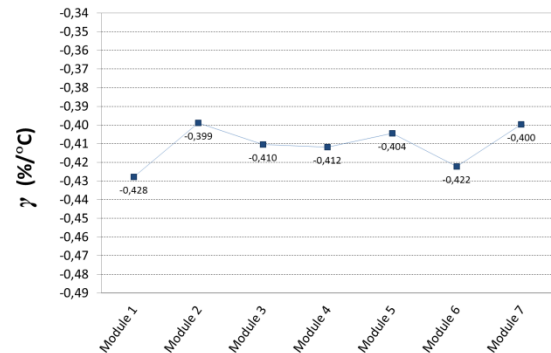


Figure 12: Power temperature coefficient γ of seven different modules from the same batch measured inside the Climatic Box.

4.3 Measurement of efficiency parameters.

Finally, taking into account the model adopted by SISIFO to describe the performance of a PV system (see second equation), it can be noticed that the energy production also depends slightly on the module behaviour related to the variation of irradiance: parameters a , b and c . These parameters can be obtained from the power measured at two other than G^* irradiance values, which must also be found at manufacturer datasheet, providing

they comply with international standards [14].

The Climatic Box allows measuring also these parameters of a single module. As it is mounted on a tracking structure it can be oriented to achieve the desired amount of irradiance during the I - V curve measurements, thanks to the external secondary solar cell. So, if the procedure explained previously for measuring the I - V curves at STC is repeated to measure power at 25°C but at lower irradiances, as for example 600 W/m² and 200 W/m², the values of parameters a , b and c can be calculated.

Fig. 13 shows the result of measuring at 25°C the set of 7 modules previously presented at three different irradiance levels: 200 W/m², 600 W/m² and 1000 W/m². So, the powers at these conditions are obtained and these values allow calculating a , b and c and, therefore, the module efficiency curve, which is presented in the graph (normalized by the module efficiency at STC). It is also represented the efficiency curve obtained from the datasheet information (power at STC, power at NOTC and reduction of module efficiency from 1000W/m² to 200 W/m² should be reported).

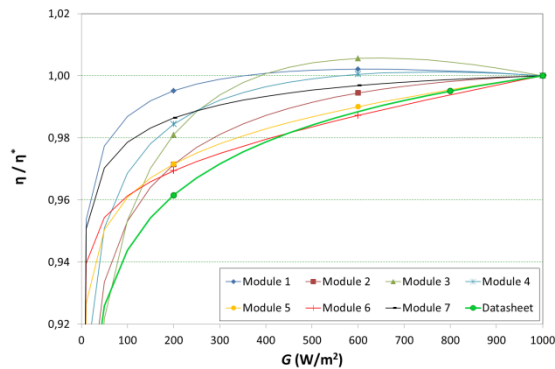


Figure 13: Efficiency curve (normalized) of seven different modules from the same batch measured inside the Climatic Box. They are obtained by measuring the PV modules at 25°C and at 1000, 600 and 200 W/m². The efficiency curve from the information of the manufacturer datasheet is also included.

As can be noticed, all the modules perform better than is reported in the datasheet; that is, this information in the datasheets uses to be conservative. Therefore, if this information is used in simulation software the final energy prediction will be less accurate. It would be better to use the average of the module efficiency curves measured over a representative sample of the PV installation to perform a more accurate simulation.

5 SUMMARY

This paper has presented a device which allows characterize on-site the behaviour of a PV module in the same place where it is installed. This device (composed by an isolated box, a manual tracker in which the box is mounted, an external air conditioning machine, four fans at the corners of the box to homogenize the temperature, nine temperature sensors, two reference cells—one external and another one inside the box—, a datalogger to record these temperatures and irradiances), in combination with an electronic I - V curve tracer, allows

measuring the I - V curve at STC, as well as the temperature coefficients and the module efficiency at different irradiances.

The temperature coefficients are needed for the calibration of reference PV modules. And both the temperature coefficients and the parameters defining the efficiency behaviour at different irradiances are very useful to reduce the uncertainty and to achieve more accurate predictions of the PV system energetic production.

Besides, all the parameters that are obtained with these measurements, which are useful for the estimation of the PV system energy production (P^* , γ , a , b and c), can be compared with the information reported in the datasheet to check if the characteristics claimed by the module's manufacturer agrees with the real behaviour.

6 ACKNOWLEDGEMENTS

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POLITÉCNICA

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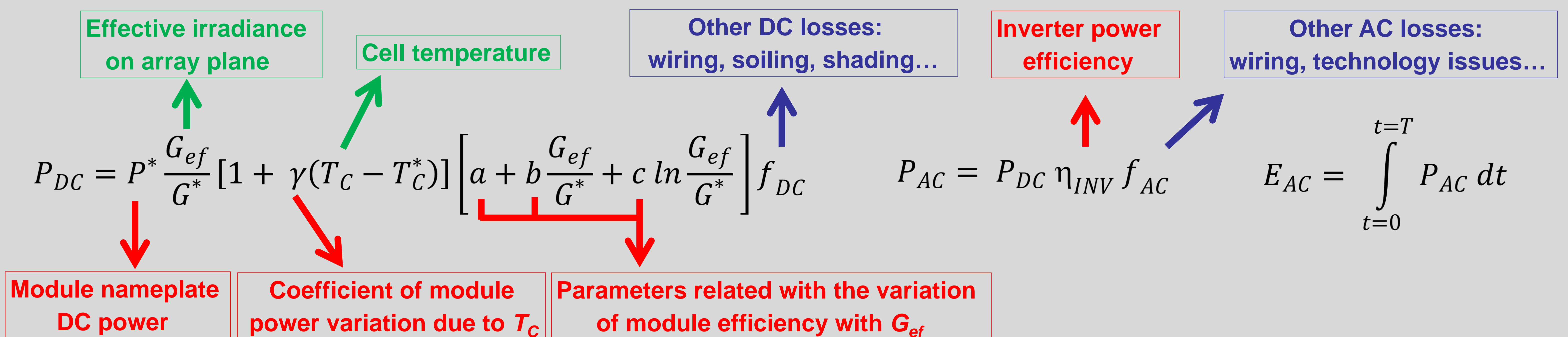
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1. INTRODUCTION

- Performance of PV installations depends on real module behaviour:
 - STC characterization (I - V curve). \longrightarrow It uses to be rigorously done always.
 - Variation of power with temperature (temperature coefficients). \longrightarrow They are barely characterized.
 - Variation of power with irradiance (efficiency).
- These characterization uses to be done at laboratories far away PV installations:
 - Expensive devices (flash-simulator, climatic chamber).
 - Transport of the modules not directly to the PV plant, at laboratories: \longrightarrow Increases the risk of breakage. \longrightarrow Increases the cost.
- PVCROPS project of the 7FP has proposed \longrightarrow Software tool to estimate energy yield production of PV system \longrightarrow Test procedures and cheap devices to measure on-site outdoors

2. ENERGY YIELD FORECAST: SISIFO

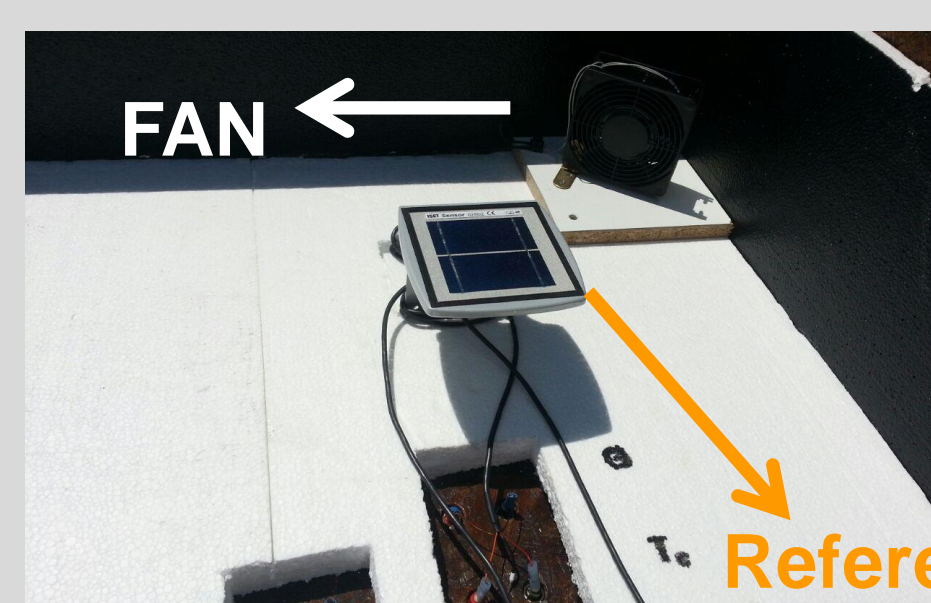
- SISIFO is a free software tool (www.sisifo.info) to simulate energy production that uses **a model based on parameters guaranteed by the manufacturers**, **a baseline losses scenario** and **operating conditions**.



- More accurate estimation of energy and lower uncertainty if \longrightarrow G_{ef} and T_C are measured with reference PV modules of the same technology. \longrightarrow P_M^* , γ , a , b and c of a representative sample of modules are measured (better than datasheet)

3. MEASUREMENTS ON-SITE: CLIMATIC BOX

- Together an electronic load to measure I - V curves and a datalogger

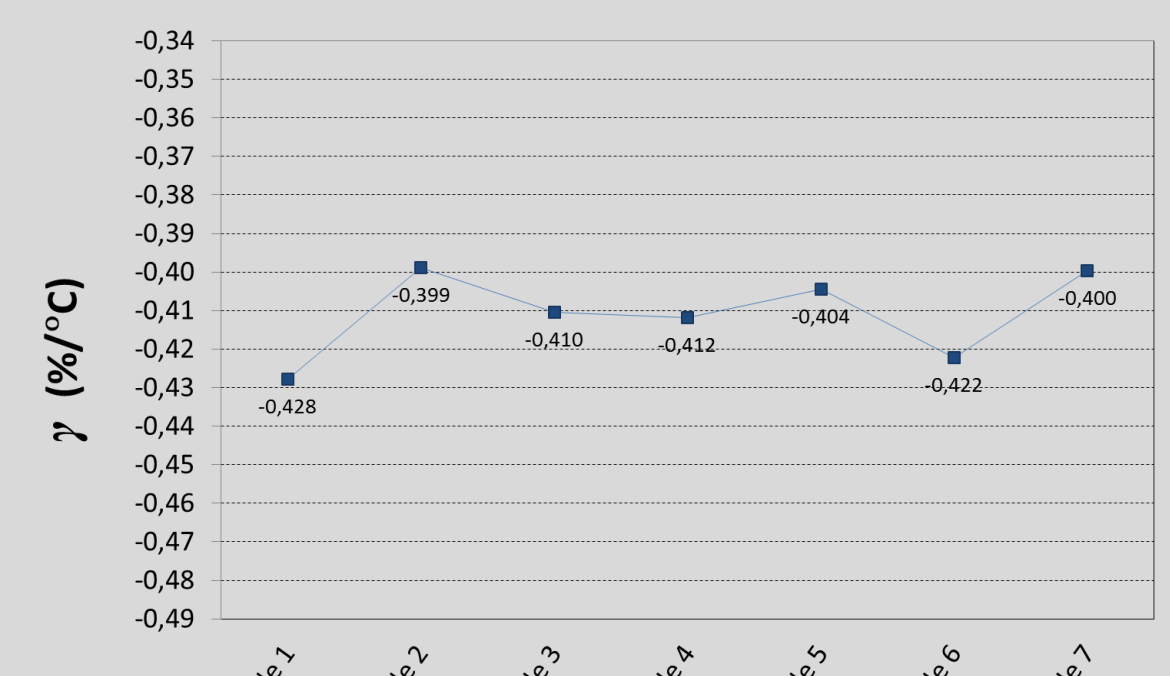
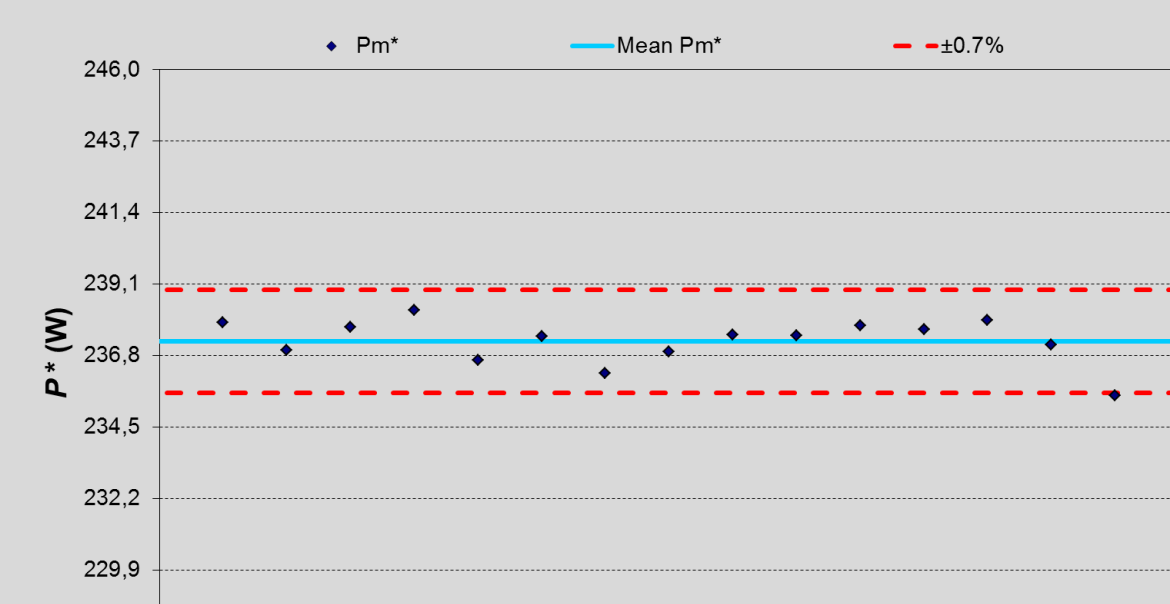
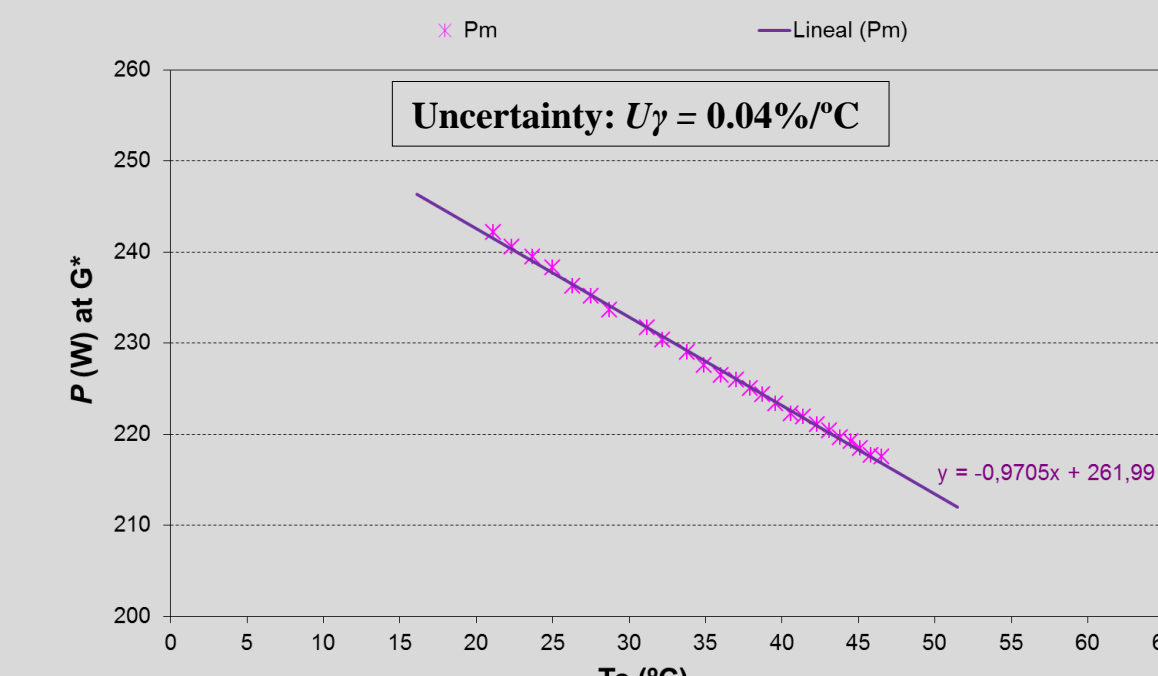
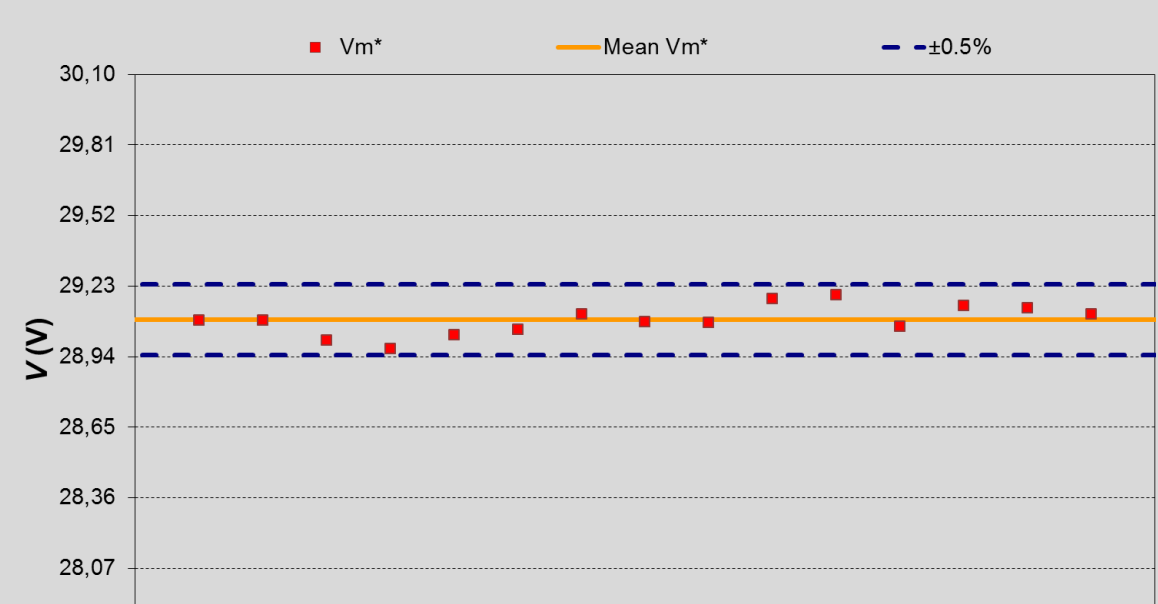
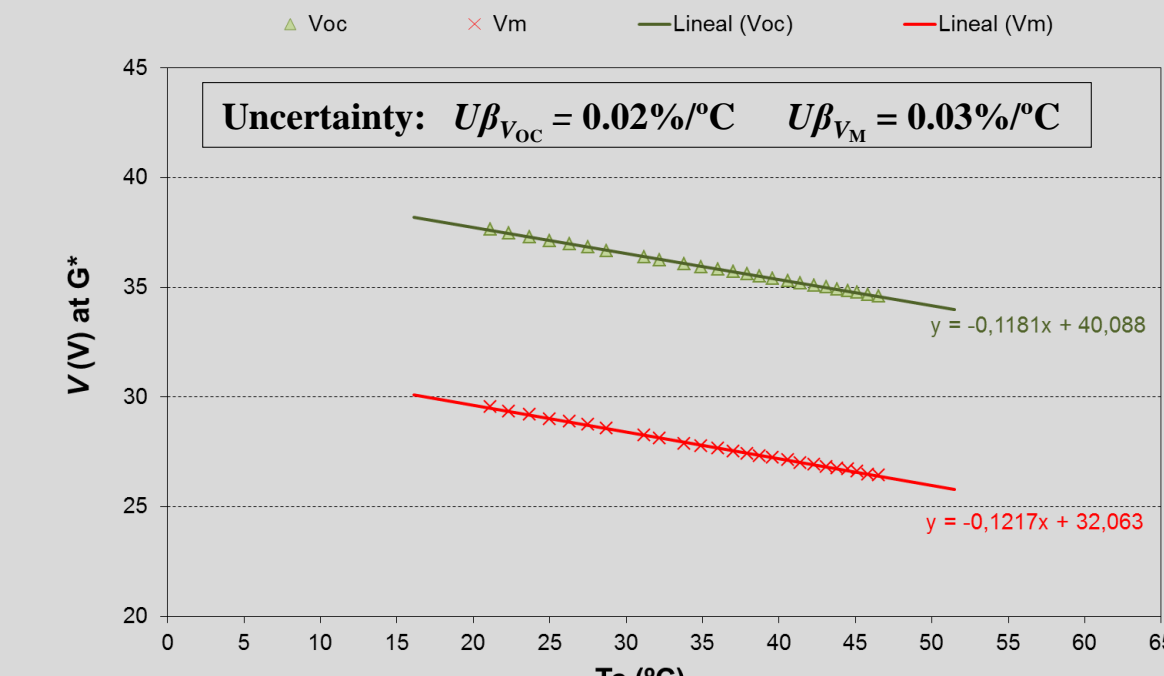
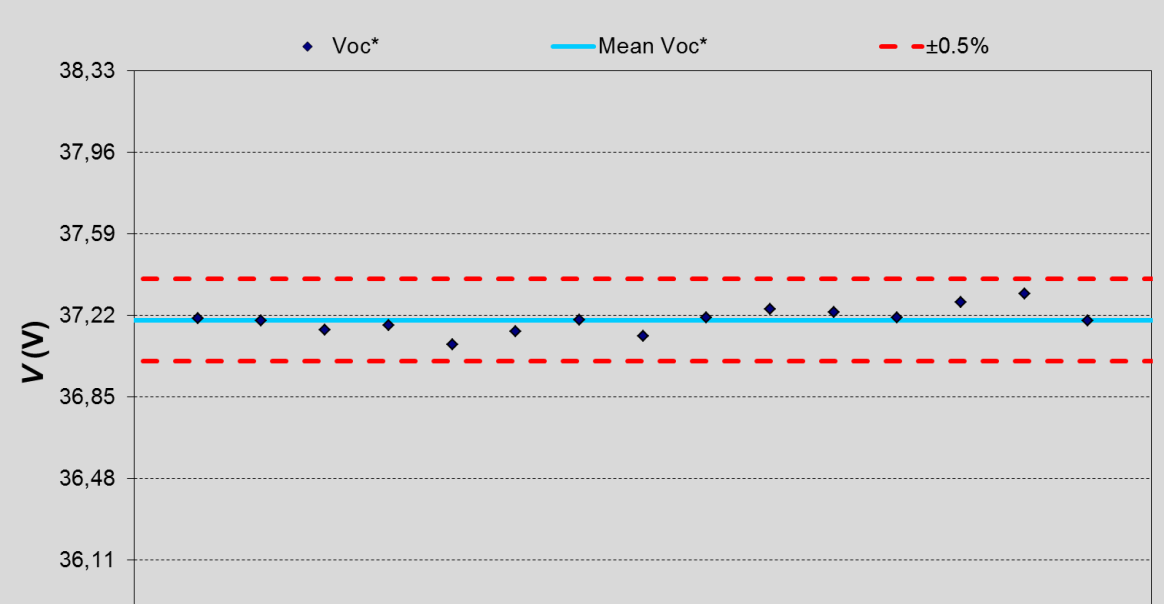
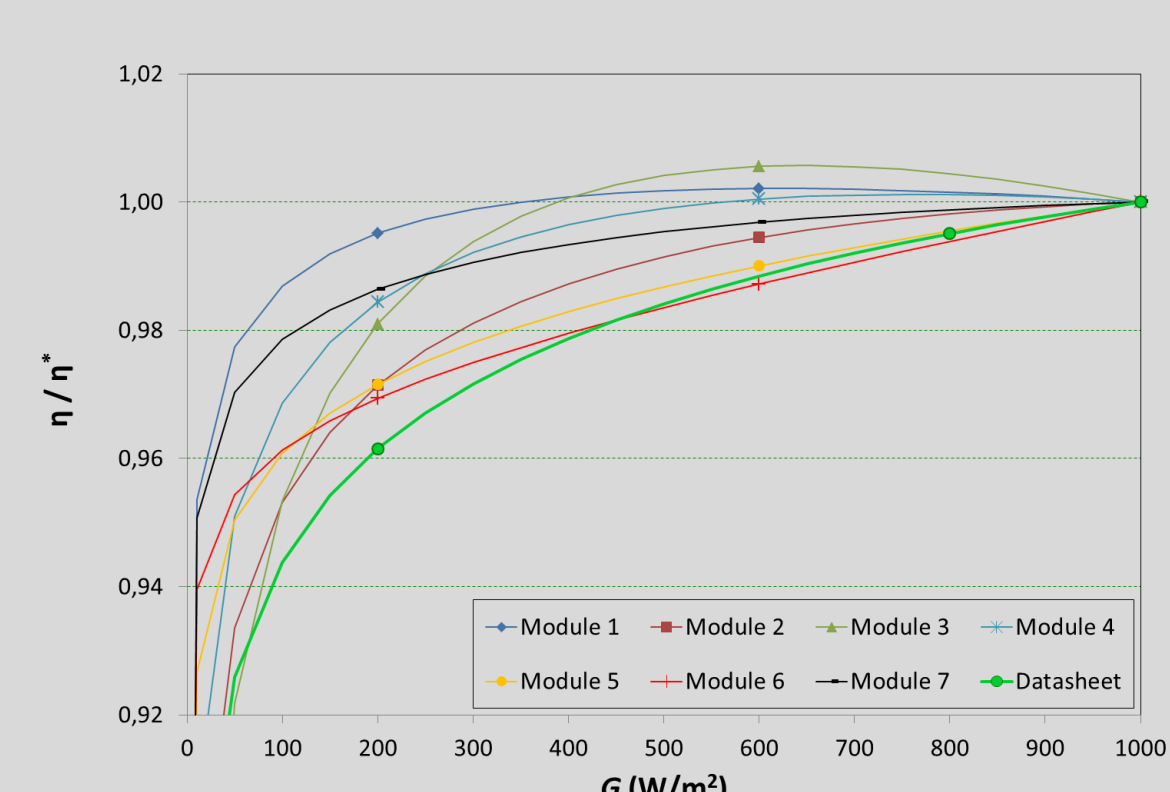
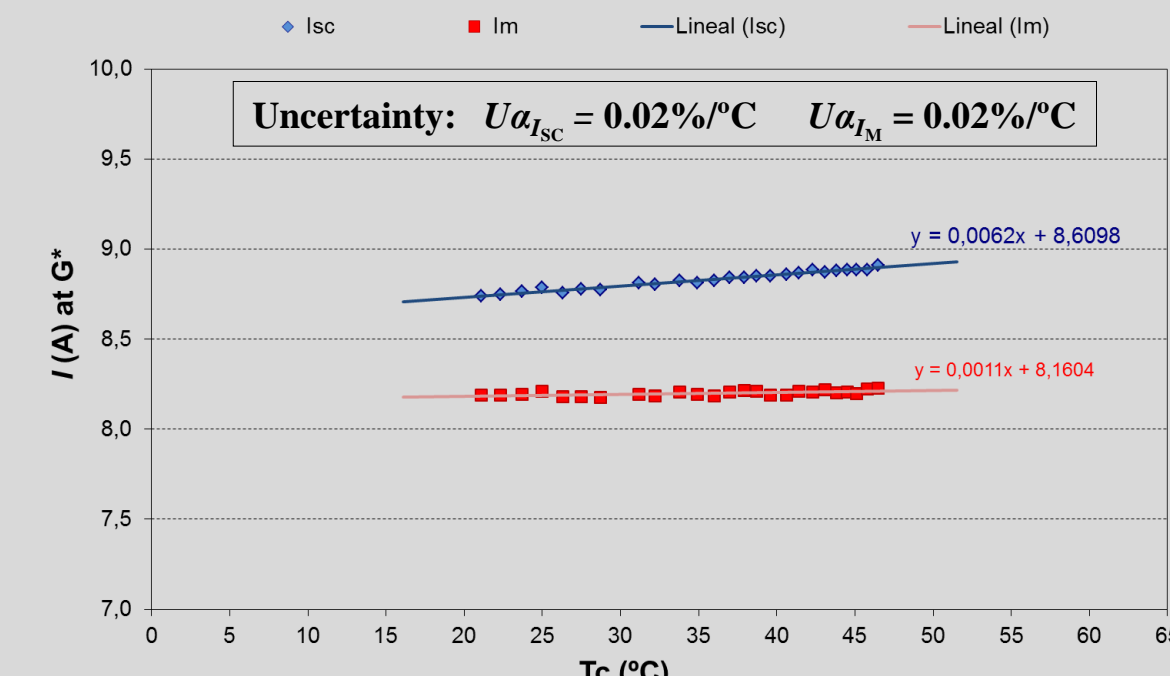
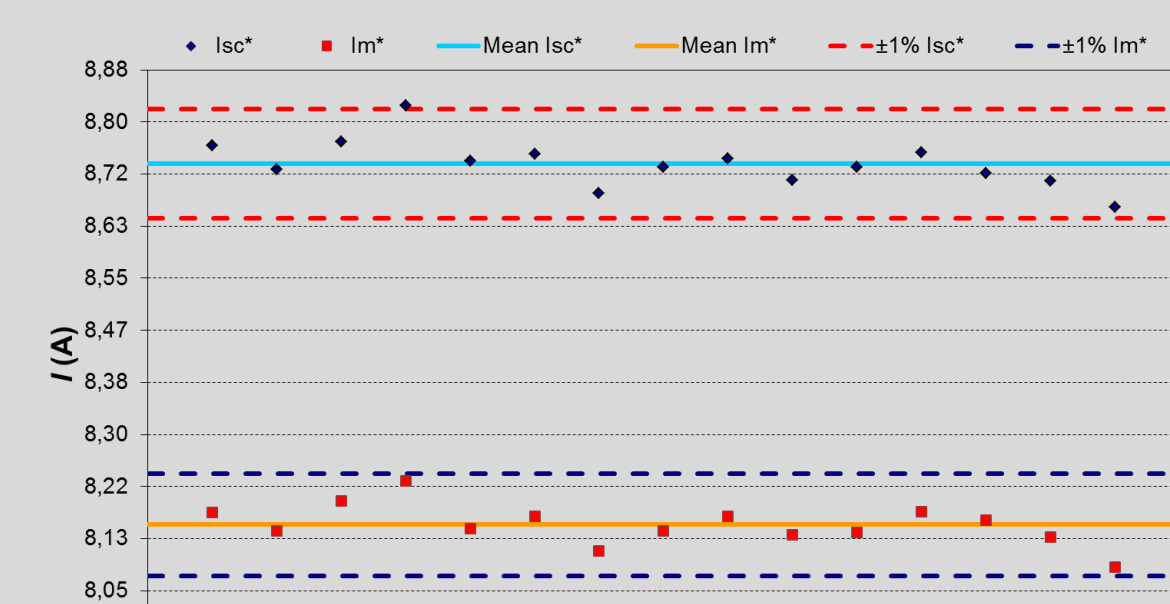


- STC characterization

(I_{sc}^* , V_{oc}^* , I_M^* , V_M^* , P_M^*)

- Temperature coefficients characterization (α , β , γ)

- Efficiency coefficients characterization (a , b , c)



We are looking you forward in the parallel event
(Thursday 17th Sept 13:20–18:30):
“PVCROPS: Novel solutions for a high PV penetration in EU electrical networks with lower LCOE”
(At 17:00: Quality control procedures for the bankability of PV plants: Software and Hardware solutions)